3D SOUND CUEING FOR THE SIMULATION OF ARTHROSCOPIC SURGERY

Loïc Corenthy[1,2], **Erik Vladimir Ortega González**[1,*], **Samir Garbaya**[1], **José Miguel Espadero Guillermo**[2]

[1]Arts et Metiers ParisTech, CNRS, Le2i
Institut Image, 2 rue T. Dumorey, Chalon-sur-Saône 71000, France

[2]Grupo de Modelado y Realidad Virtual, Universidad Rey Juan Carlos
Av. Tulipán s/n. Móstoles 28933, Madrid, Spain

[*]Correspondig author: erikvladimir@gmail.com

ABSTRACT

Arthroscopic surgery offers many advantages compared to traditional surgery. Nevertheless, the required skills to practice this kind of surgery need specific training. Surgery simulators are used to train surgeon apprentices to practice specific gestures. In this paper, we present a study showing the contribution of 3D sound in assisting the triangulation gesture in arthroscopic surgery simulation. This ability refers to the capacity of the subject to manipulate the instruments while having a modified and limited view provided by the video camera of the simulator. Our approach, based on the use of 3D sound metaphors, provides interaction cues to the subjects about the real position of the instrument. The paper reports a performance evaluation study based on the perception of 3D sound integrated in the process of training of surgical task. Despite the fact that 3D sound cueing was not shown useful to all subjects in terms of execution time, the results of the study revealed that the majority of subjects who participated to the experiment confirmed the added value of 3D sound in terms of ease of use.

1. INTRODUCTION

Arthroscopic surgery is one kind of Minimally Invasive Surgery (MIS). MIS can be defined as a set of therapeutic techniques and diagnosis methods in which direct vision, or endoscopy or any other imaging technique uses natural ways or minor incisions in order to introduce tools and to operate in different parts of a human body [1]. Avoiding large incisions in the patient body leads to the following benefits: less bleeding during the operation, no unpleasant scars after the intervention and the reduction of infection risks. Added to these benefits MIS allows cheaper and shorter hospitalization.

Depending on the region of interest on the body, MIS includes different operating techniques such as laparoscopy (when dealing with the abdomen) and arthroscopy (when dealing with joints) among others. Minimally invasive surgery involves more complex gestures than classic surgery. Indeed, the operation has to be performed with a limited and modified point of view (from a video camera). Therefore, the surgeon has to perform triangulation gesture which means that he has to position a tool in a 3 dimensional space without having direct view. This visual restriction makes the learning process difficult.

Helping the surgeon apprentices to master these techniques can be achieved by using surgical simulators. This paper presents an approach that integrates audio stimulation in surgical simulator. 3D audio is a mature technology concerned with reproducing and capturing the natural listening spatial phenomena. The contribution and pertinence of 3D audio stimulation in interactive systems is an interesting scientific problem.

The literature research revealed that 3D audio has been historically used as a mechanism limited to spatializing existing sound effects. In general, sound spatialization is used to improve the realism of the interaction and consequently, the sensation of immersion in virtual environment. The inclusion of 3D sound in VE in order to extend interaction capabilities was not investigated by the published research.

Ortega-Gonzalez et al. [2] studied the contribution of 3D auditory stimulation in interactive systems. They proposed the approach of 3D sound metaphors. This approach is based on spatial sound sources enriched with metaphoric cues. The authors of this paper considered that 3D sound metaphors allow accurate 3D position cueing that could be useful for assisting manipulation tasks in virtual environment. This approach is innovative in the sense that it is based on the combination of audio cueing using 3D sound metaphors.

The focus of this paper is to investigate the contribution of 3D sound to facilitate triangulation gesture in arthroscopic surgical simulator. This paper is organized as follows: section 2 presents a selection of the related work, the experimental platform is described in section 3. Section 4 presents the proposed approach. The experimental design is described in section 5. The results of the experimental work are presented in section 6 and finally, section 7 presents the conclusion and research perspectives.

2. RELATED WORK

2.1. Surgical simulation

Surgical simulation is useful because it avoids the use of patients and allows the trainees to practice surgery before treating humans [3]. Currently, there exist different simulators for MIS operations.

Moody et al. [4] developed the Warwick Imperial, Sheffield Haptic Knee Arthroscopy Training System (WISHKATS) used for the triangulation and arthroscopic diagnosis of the knee. In the same context, Sherman et al. [5] developed a training virtual environment called Knee Arthroscopy Training System (VE-KATS).

The interfaces between the subject and these devices are designed to provide a realistic experience. Thus, the interaction is mainly based on haptic and visual sensation.

The system described in this paper is based on the work developed by Bayona et al. [6], dedicated to shoulder arthroscopy training system with force feedback. One of its main applications is the training on triangulation gesture. This simulator was developed with a modular architecture. It includes different modules such as the simulation kernel and the interaction system. These modules provide the graphic rendering and the collision detection functionalities which are necessary for the haptic rendering. The technical contribution of this paper is to integrate spatialized sound into this architecture in order to provide the trainee with sound feedback for 3D audio cueing.

Bayona et al. [7] carried out an evaluation study on 94 arthroscopists specialized in orthopaedics and traumatology.

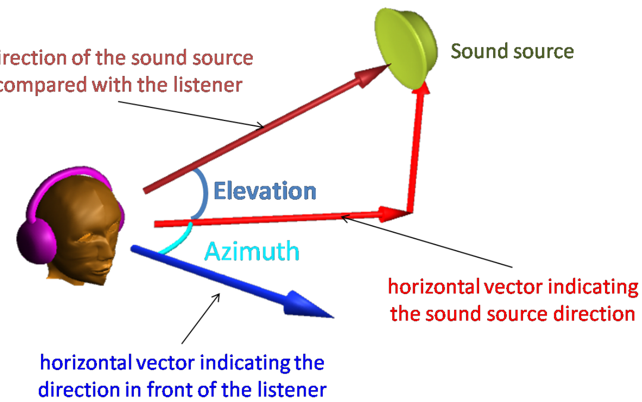

FIGURE 1. THE AZIMUTH AND THE ELEVATION OF A SOUND SOURCE

This study was conducted using the commercial version of the same simulator used in this paper.

The evaluation study showed that:

- ◇ the simulator is more beneficial to inexperienced surgeons than experts
- ◇ practicing triangulation is qualified as important by experts but not by inexperienced surgeons.

Based on these results, the work described in this paper involved novice subjects practicing triangulation gesture.

2.2. 3D Sound: HRTF and metaphor

3D sound refers to the techniques and methods used to reproduce the natural human hearing conditions. 3D sound particularly takes into account the spatial proveneance of the heard sound and the environment effects. The listening place and the listener ears characteristics are important elements of artificial spatial hearing.

According to the work published by Ortega-Gonzlez et al. [8] a 3D sound is characterized by its basic perceptible features (a.k.a. high level characteristics): depth, reverberation and directivity. The first characteristic refers to the distance between the sound source and the listener. The second takes into account the modification due to the listening environment, i.e. mainly the reverbering effects. The third characteristic refers to the direction of provenance of the sound source. This direction is defined by two angles: the azimuth and the elevation. They represent the deviation angles in the horizontal and vertical plane respectively as shown in figure 1.

The directivity of a spatial sound source is commonly simulated using the Head-Related Transfer function (HRTF) theory [9, 10]. The HRTF describes how the reflections and refractions due to the pinnae modify the sound signal before it reaches the eardrum. Begault [11] stated that the HRTF represents the

(a) *Simulator Frontal View* (b) *Simulator Lateral View*

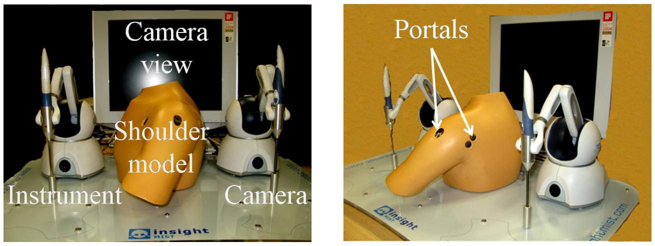

FIGURE 2. THE MAIN COMPONENTS OF THE SIMULATOR

(a) *Subject View (from the camera)* (b) *Operator View (external)*

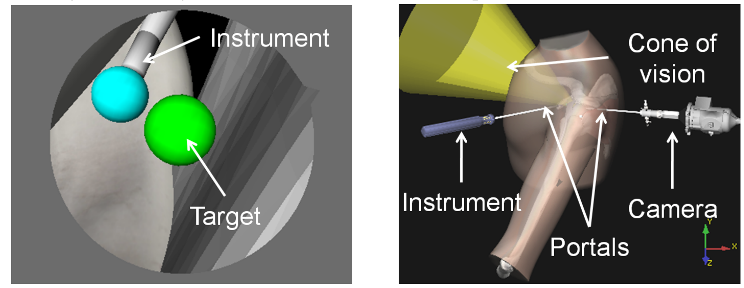

FIGURE 3. SUBJECT AND OPERATOR VIEWS

spectral filtering which occurs before the sound arrives to the internal eardrum. This transfer function is modeled by measuring how a particular listener ear modifies the sound signal (acts like a filter). The HRTF is basically a discrete transfer function. It gives information for a set of discrete points around the listener which are all the possible origin position for the sound source.

An original approach to the 3D sound synthesis is to add to the use of the HRTF, other modifications described by metaphors [2]. These metaphors also are filters which modify the sound. The main difference with the HRTF is that they are not designed to describe the natural listening conditions but to provide enriched cues. Thus they are not necessarily based on a realistic model. In the work described in this paper a model combining the use of the HRTF and sound metaphors is used.

3. EXPERIMENTAL PLATFORM

3.1. Arthroscopic Surgery Simulator

The experiments reported in this paper were carried out with surgery simulator using a shoulder model. The simulator is a prototype system of commercial version named "Insight$_{\text{ArthroVR}}$", distributed by GMV Innovating solutions [12]. It combines virtual reality and computer-aided learning techniques to simulate the key aspects of arthroscopic surgery.

The platform main elements are the following (figure 2a and figure 2b):

- ◇ A joint shoulder plastic model at scale 1:1. The shoulder model was equiped with portals (entrance points through which the instruments are inserted into the shoulder). Their positions correspond to the common positions used during real surgery.
- ◇ Two haptic devices (Phantom Omni). A metallic extension was added to each of the phantoms. They represent the instrument and the camera to allow more realistic manipulation.
- ◇ A support platform for the positioning of the phantoms and the shoulder model. The platform allowed two position configurations for each phantom.
- ◇ Two LCD monitors, one for the subject and another for the experimenter also known as the operator. On the subjects monitor, the image of the camera was displayed whereas on the operator's monitor, one could see an external point of view of the 3D scene (figure 3a and figure 3b).

The camera image consists of a three dimensional view of the relevant elements inside the shoulder (bones, muscles and tendons) corresponding to the image the subject would see during a real surgery using arthroscopic camera. The rendering was made using the library Coin3D (figure 3). For the used configuration, the phantom on the right is used as a camera and the phantom on the left represents the instrument (figure 2a).

3.2. The integration of 3D sound

In order to provide the subject with audio cueing, a module of 3D sound was integrated into the surgical simulator "Insight$_{\text{ArthroVR}}$". Spatialized sound stimulation was implemented by combining 3D sound metaphor and the HRTF. The implemented HRTF was taken from the work of Gardner and Martin [10]. Figure 5 shows the architecture of this module.

3D sound metaphors were originally created to assist the subject in localizing sound sources. This is carried out by dynamically applying sound effects to an audio stimulus depending on the subject activity. The idea is to reinforce and to enrich directivity properties of a spatial audio stimulus by applying certain sound effects to the stimulus. We privileged the intelligibility of cues over the realism.

The implementation of the metaphor and the HRTF was carried out using FMOD library. This library offers graphic interface (FMOD Designer), which enables applying sound effects functions of specific parameter by adjusting a curve of behavior (figure 4a).

Table 1 summarizes the complete set of cues and their associated sound effects and spatial features that form the employed 3D sound metaphor. For each cue an associated audio effect and the corresponding spatial feature are specified. The relationship of each effect and the corresponding spatial feature is specified by a behavior curve.

The term verticality refers to whenever the sound source is *(a) FMOD Designer interface* *(b) Reverberation curve*

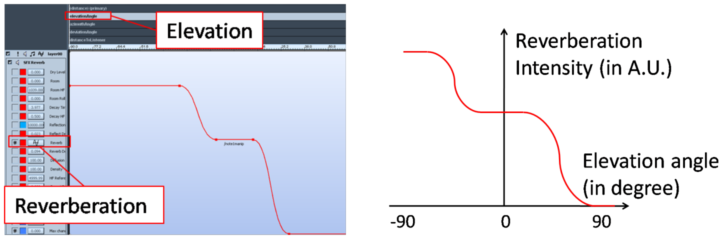

FIGURE 4. METAPHOR CURVE IN FMOD DESIGNER

located above or below the reference plane associated to the head of the subject. Horizontality refers to the horizontal angular deviation perceived by the subject. The term of frontality refers to the ability of the subject to distinguish whether the sound source is located in the front or at the back of the subject. Angular proximity refers to the capacity of accurately determining the provenance of the sound source when the absolute angular deviation is small (less than ten degrees).

The verticality cue was defined by a curve specifying the amount of echo applied to the stimulus according to the changes in the elevation. If the sound source was below the virtual listener ($-90^\circ < elevation < 0^\circ$), the subject could hear a sound with reverberation whereas when the sound source was above the virtual listener ($0^\circ < elevation < 90^\circ$), the subject could not hear any reverberation (figure 4b). This information is intended to help the subject in localizing sound sources.

TABLE 1. PERCEPTUAL CUES OF THE METAPHOR

Cue	*Associated sound effect*	*Associated spatial feature*
Verticality	Reverb	Elevation
Horizontality	Attenuation	Azimuth
Frontality	Occlusion	Azimuth
Angular proximity	Sharpening	Elevation and azimuth
Depth	Attenuation	Distance

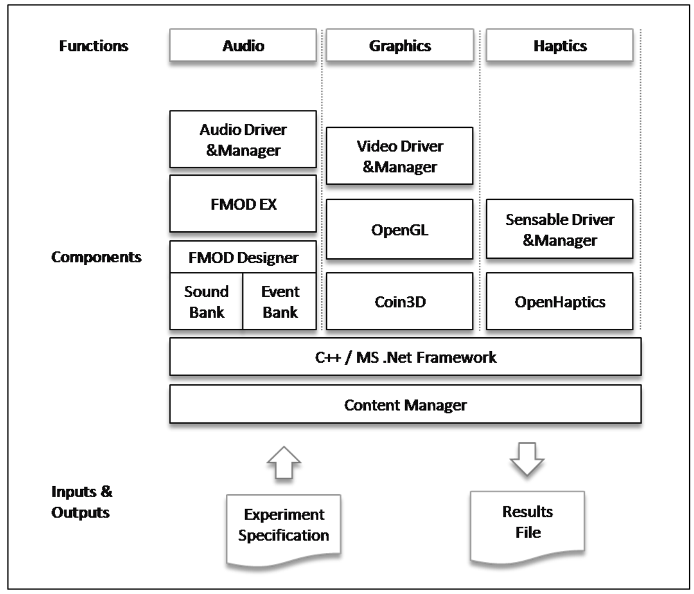

FIGURE 5. SOFTWARE ARCHITECTURE

4. APPROACH: 3D SOUND TO ASSIST THE SUBJECT IN MANIPULATING SURGICAL INSTRUMENT

In the context of Minimally Invasive Surgery, the surgeon has not direct visual feedback of the instruments that he is manipulating. In the common approach, the surgeon has first to localize the position of the camera inside the shoulder by recognizing the visible elements. Then the camera is used to localize the target which is represented by a sphere. The subjects visual feedback is restricted to the cone of vision. Normally, the subject has to perform several attempts trying to put the instrument in the cone of vision of the camera.

By using the spatialized audio stimulation, the process is modified as follows: once the subject has identified the target, he uses the auditory information in order to put the instrument into the cone of vision. The auditory information assists the subject in the manipulation of the instrument relative to the cone of vision of the camera.

4.1. Sound stimulus

The stimuli used in the research of auditory stimulation are commonly of four kinds: voices (human speech and animal sounds), music, noise and briefs (either impulses or clinks). The used sound was selected based on the work of Doerr et al. [13] and Silzle et al. [14] as well as on a series of informal tests. A brief sound was chosen with a duration of 0.5 seconds approximately. Its waveform has a clink shape and it is reproduced continuously. The main criteria for selecting this kind of shape is that brief stimuli have evidently less information to be decoded compared to a voice signals and that it could be more intelligible (easy to recognize), less diffused and probably less annoying than almost any kind of noise signal. Music impulses were discarded because they also commonly demand more decoding effort and because their choice can be controversial (subjects risk to be highly influenced and even perturbed by their personal preferences). This situation can affect the performance in a manner difficult to predict. We consider that clink stimuli are more neutral in this aspect.

We consider that noise signals are annoying because they could be commonly associated to technical problems (i.e. communication interruption and corruption) and because we noticed that they are considered unpleasant for most subjects who participated in the previous tests. Silzle et al. [14] found that the use of clink stimuli allows reducing the variability of the localization error particularly for the elevation parameter compared to noise and speech sounds. Consequently, brief sounds are less diffuse. Noise sounds can also transmit a sensation of disorder that would be naturally not appropriate for the application described in this paper. Finally, the use of brief sounds allows the simplification of the spectral analysis and the adjustment of curves that define the metaphoric cues. This is important because most of the cues are applied as frequency filters.

The comparison of different sound stimuli is not the scope of the work reported in this paper. The use of other stimuli different than the stimulus adopted in this work, will have undoubtedly an effect on performance. However, the considered criteria and the previous tests provided evidence that the use of this kind of stimuli is appropriate to accurate sound source localization. Sound stimulus is enriched with the metaphor cues and spatialized with the HRTF. This additional information is intended to help subject to put to adjust the instrument in the cone of vision of the camera.

4.2. Mapping sound source

The positions of the real instruments into the shoulder model (figure 7) correspond to the position of the virtual instruments in the virtual scene (figure 3b). The virtual auditory scene is made by the virtual listener and the virtual sound source. In order to use the sound stimulus to provide position cues, the virtual listener and the virtual sound source are associated to the positions of the camera and the instrument respectively.

The sound source is associated to the instrument extremity and follows its movements. The virtual listener was placed into the vision cone of the camera at 3.5 cm away from the camera (figure 6). The virtual listener follows the movements of the camera (translations and rotations) but he is always oriented in the same direction as the subject. This artifact allows the virtual listener to have the same orientation reference system as the real listener. The subject can refer to the direction of the sound source to determine the position of the instrument relative to the camera. The experimental work reported in this paper consist of determining if this auditory information assist the subject to adjust the instrument in the cone of vision of the camera.

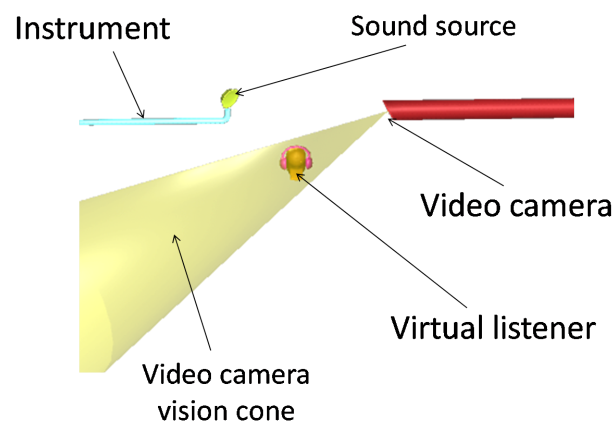

FIGURE 6. VIRTUAL LISTENER AND SOUND SOURCE MAPPING

5. EXPERIMENT DESIGN
5.1. Hypothesis

An experimental protocol was defined in order to determine the contribution of the 3D sound cueing for surgery training. The following experimental hypotheses are defined :

◇ Spatialized sound affects the subject performance in learning arthroscopic surgery. It is possible to determine if 3D sound assists or perturbs the subjects.
◇ Spatialized sound affects the subject perception. The subject is able to evaluate the benefits of integrating spatialized sound in surgical simulator and could evaluate its ease of use.

5.2. The experimental task

The protocol was based on a training exercise implemented on the simulator: localize and touch a series of targets (spheres) located at predefined positions inside the shoulder muscular and skeletal structure.

Figure 7 shows one subject executing the task in the condition including spatialized audio stimulation. In order to perform the triangulation, the subjects were recommended to adopt the the following strategy :

◇ First localize with the camera a red sphere into the scene which represents the target. The red color indicates to the subject that the camera is not in a correct position to visualize the target.

◇ Once the target is visualized big enough on the monitor during more than 2 seconds, the sphere becomes green and the subject has to put the tissue manipulator into the vision cone of the camera (triangulation phase) without moving the camera point of view.
◇ Finally, seeing both the tissue manipulator and the sphere on the monitor, the subject has to touch the sphere with the instrument.

5.3. Group of subjects

Eleven subjects (8 male and 3 female) participated to the experiment. They do not have previous experience with phantom manipulation. The subjects do not have particular experience of arthroscopic surgery which convenient for the experiment since the simulator is designed for apprentices. Before starting the session, the experimenter explains the system and allows the subjects a practicing session not taken into account in the measurement of performance. For performance evaluation, the execution time was measured but task precision was not taken into account because it is considered not important for the evaluation of this task. The ease of use and the usefulness of the technique were recorded.

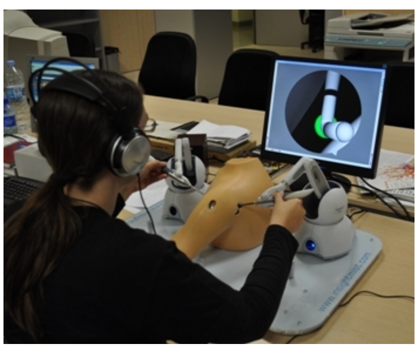

FIGURE 7. EXPERIMENTAL PLATFORM

5.4. Objective variable

The task execution time are measured for the second and the last phases of the exercise, i.e. when the subject tries to put the tissue manipulator into the vision cone and touch the sphere. In order to restrain the measurement to the two last phases, we had first to make sure that the subject positioned the camera with the appropriate point of view on the sphere. This was achieved with changing the color of the sphere. Once the sphere becomes green, the time measurement starts and continues until the subject succeeded to touch the sphere.

5.5. Experimental conditions

During the experiment the subject has to execute the task with five different targets located in different positions. Two experimental conditions were defined:

◇ **Condition 1**: the subject has to perform the task with 3D sound stimulation,
◇ **Condition 2**: the subject is asked to perform the task without 3D sound stimulation.

The task is repeated five times for each experimental condition. In order to avoid carry over effect, the experimental conditions are presented for each subject in random order and the locations of the spheres for the experimental condition 1 are different from those of condition 2

5.6. Subjective evaluation

In order to obtain the feedback from subjects, the subjects who participated to this experiment were asked to give their appreciation about the contribution of audio stimulation in this application. The feedback was obtained using a questionnaire made of one question and two assertions.

The question is: in terms of ease of use, how better is the task condition that includes 3D sound compared to the task condition without 3D sound?

The two assertions are:

◇ The sound was useful during the phase of moving the tissue manipulator into the camera vision cone.
◇ The sound was useful to touch the sphere.

The obtained answers were structured following the Lickert 7 score system. Thus, there were negative, neutral or positive options.

6. DATA ANALYSIS AND RESULTS

6.1. Performance evaluation

Figure 8 shows the mean execution time for each subject, in both experimental conditions. The subjects are classified into two distinct groups: Group 1 is made of subjects who succeeded to complete task in a shorter time in condition 1 than in condition 2. Group 2 is made of seven subjects who performed the task with a longer time in condition 1 than in condition 2.

Figure 9 shows the relative difference in percentage of task execution times obtained by the following equation:

$$\frac{t_N - t_S}{t_N} \tag{1}$$

where t_S and t_N are the execution times for the condition 1 and the condition 2 respectively. The positive values refer to the subjects

TABLE 2. ANSWERS DISTRIBUTION CONCERNING THE QUESTION

Answer categories	*Answer distribution in %*
Much worse	0.0%
Worse	0.0%
Slightly worse	0.0%
Identical	0.00%
Slightly better	36.4%
Better	45.5%
Much better	18.2%

TABLE 3. ANSWERS DISTRIBUTION CONCERNING THE FIRST ASSERTION

Answer categories	*Answer distribution in %*
Much worse	0.0%
Worse	0.0%
Slightly worse	0.0%
Identical	0.0%
Slightly better	27.3%
Better	36.4%
Much better	36.4%

who completed the task in a shorter time in the experimental condition 1 than in the condition 2. The negatives values refer to the subjects who completed the task with a longer time in condition 1 than in condition 2

These results show that 3D sound allows shorter task execution time but this does not apply for all subjects. Moreover, 3D sound does not perturbe the subjects of group 2 at the point to slow down their task execution time. The fact that only small number of subjects were able to take benefit from 3D sound cueing we can conclude that even if spatialized sound stimulation does improve the subject performance in terms of task execution time, the mapping of the interaction technique was not clear enough to be easily understood by all subjects.

6.2. Evaluation of the ease of use

Table 2 shows the results of the subjective evaluation. The majority of the subjects consider the integration of spatialized

TABLE 4. ANSWERS DISTRIBUTION CONCERNING THE SECOND ASSERTION

Answer categories	*Answer distribution in %*
Much worse	9.1%
Worse	18.1%
Slightly worse	9.1%
Identical	27.3%
Slightly better	27.3%
Better	9.1%
Much better	0.0%

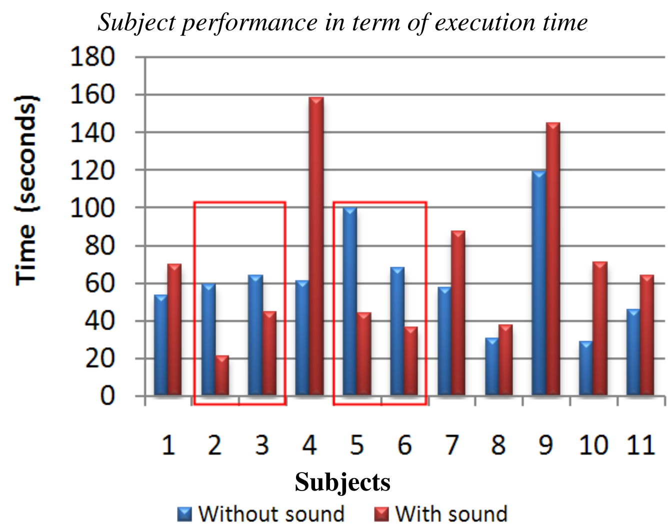

FIGURE 8. TOTAL MEAN TIME FOR EACH SUBJECT

sound in the interaction technique contributes to the ease of use of the simulator.

Table 3 shows the subjects answers concerning the first assertion. All subjects consider that 3D sound has positive effect on triangulation gesture. Moreover, 60% of the subjects consider this effect as better or much better.

Table 4 shows the results of the second assertion. According to the feedback obtained from the subjects, spatialized sound assists the subject in the triangulation phase but not it does not provide any help to touch the sphere.

7. CONCLUSIONS

This paper presents a new approach of 3D audio cueing applied to virtual arthroscopic surgery. An interaction technique

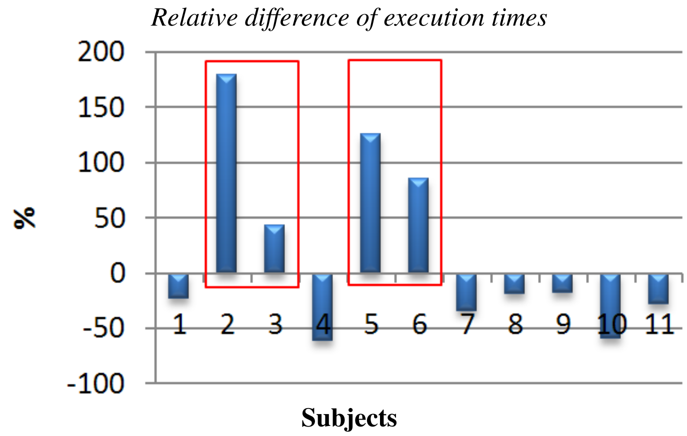

FIGURE 9. RELATIVE DIFFERENCE OF THE EXECUTION TIMES FOR EACH SUBJECT

based on 3D sound stimulation was defined.

The subject performance evaluation revealed that 3D sound contributes to the triangulation gesture. On the other hand, the results showed that small number of subjects succeeded to complete the task faster when 3D sound is included in the surgical simulator. These results lead to the conclusion that the mapping technique used in this experiment must be redesigned to improve the ease of use of the system.

During the experiments, we noticed that subjects used spatialized sound as a guide to put the instrument in the cone of vision of the camera. In the condition where the spatialized sound is not included in the simulator, subjects moved the instrument in a way of random research. The introduction of 3D sound in the simulator allowed the subject moving the instrument in the shoulder following optimized trajectories. In the perspectives of this research we intend to redesign the mapping of the interaction technique and perform an evaluation of the surgery based on the precision of the gesture.

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